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Analysis of CCS diffusion for CO_2 emission reduction considering technology diffusion barriers in the real world

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Abstract

Technology diffusion barriers exist widely in several global warming mitigation technologies. Carbon dioxide capture and storage (CCS) is expected as a cost effective technology for ambitious CO_2 emission reduction. However, large barriers will exist when private sectors invest in CCS in the real world. In this study, a global energy systems model, which the authors refer to as DNE21+, is used to analyse this issue. Our evaluation indicates that technology diffusion barriers have a significant impact on the diffusion of CCS technology. Bottom-up type policy approach for removing the technology diffusion barriers and improvements in the liability for very long term CO_2 storage and public acceptance will be important to achieve the widespread use of CCS.

Keywords: Climate change mitigation; Carbon dioxide capture and storage; Technology diffusion barriers; Implicit discount rate; Energy systems model

1. Introduction

Global CCS (Carbon capture and storage) institute reported that the capacity of large-scale integrated project of CCS in operation in 2011 was about 20MtCO_2/yr (Global CCS institute. [1]). This capacity is very small compared with current CO_2 emission, because there is a gap between CCS cost and carbon price at present. A cost estimation of CCS from supercritical pulverized coal power plants is \$60/tCO_2-\$65/tCO_2 (Herzog. [2]), while the current carbon price in EU-ETS, for example, is below \$10/tCO_2.

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However, cost reduction and energy efficiency improvement of CCS will be achieved by R&DD efforts. In addition, the carbon price for 450ppm CO_2eq is \$65/tCO_2-\$95/tCO_2 in 2030 and \$95/tCO_2-\$120/tCO_2 in 2035 (OECD/IEA. [3]). Therefore, CCS is expected to be a keen technology for ambitious CO_2 emission reduction efforts in future.

On the other hand, technology diffusion barriers have been observed in several global warming mitigation technologies. For example, technologies for energy efficiency improvements are not necessarily adopted even if adoption of those is cost efficient activity. Sorrell et al. [4] reported the reasons of this activity by perspective; economic perspective (investment risk, access to capital for investment, imperfect information for decision making, etc.), behavioural perspective (credibility of information, inertia, etc.), and organisational perspective (power of energy manager within an organisation, corporate culture). Consideration of these barriers is important.

Technology diffusion barriers to CCS will be large (Flannery [5] has pointed out the barriers of CCS deployment generally.). For example, the reason to utilize CCS is to reduce CO_2 emission by climate policies, although some exceptions exist (e.g., enhanced oil recovery operation). When climate policies are unstable, investment risks are very high compared with other major global warming mitigation options, e.g., high energy efficient technologies (see Oda et al. [6]). In addition, uncertainties of geological storage will be larger than those of engineering plants. Liability for very long term CO_2 storage will be important for CCS, while the large-scale CCS is not an experienced technology at this time. Furthermore, public acceptance issues will be also a risk in the business of CCS.

The above mentioned technology diffusion barriers have been usually measured as implicit discount rates for investment in technologies. The measured implicit discount rates are much higher than social discount rate. The implicit discount rate includes not only social discount rate, but also several kinds of risk judgements discussed above. High discount rate induces high annualized costs for investment, and cost effectiveness is reduced compared with evaluation when low discount rate is adopted. The implicit discount rates were used as assumption of a world energy systems model, which the authors call DNE21+. This model is an inter-temporal linear programming model for assessing global energy systems and CO_2 emission reduction, in which the sum of the discounted world total energy systems costs are to be minimized. Three cases were assumed for the technology diffusion barriers of CCS technologies. In one case, the technology diffusion barriers to CCS were assumed to be same with other technologies and common implicit discount rates with other technologies were adopted. In other two cases, pessimistic prospects of the technology barriers to CCS were assumed and those were set up as penalties on the implicit discount rates for CCS technologies.

Section 2 describes the model and scenarios in our analysis, followed by the model results and discussion in Section 3. Section 4 provides conclusion.

2. Assessment model

2.1. Overview

The DNE21+ model (Akimoto et al. [7]) is an inter-temporal linear programming model for assessing global energy systems and global warming mitigation. In this model, the sum of the discounted world total energy systems costs is to be minimized. The model covers the time range covering the first half of the 21st century, with the representative time points of 2000, 2005, 2010, 2015, 2020, 2025 2030, 2040, and 2050. The model consistently represents energy systems (e.g., capacities of energy-related facilities, and performances and costs of various technologies) in terms of the amounts of production activity (e.g., the production amount of crude steel), the amount of service activity (e.g., the amount of traffic service in the transportation sector), and the final energy demands in other top-down sectors that are met by a minimum cost combination of technologies. When any emission restriction (e.g., carbon taxes) is applied, the model specifies those energy systems whose costs are minimized and which still meet all the assumed requirements. The salient features of the DNE21+ model are as follows:

(1) The world is divided into 54 regions in country level. To take into consideration the transportation of energy and CO_2, large countries such as the United States, Canada, Australia, China, India, and Russia are further disaggregated into several regions. This detailed regional segregation enables us to perform our analysis while taking regional differences into consideration.
(2) The energy supply sectors are connected to the energy end-use sectors, and the lifetimes of facilities are taken into account, so that assessments are made while maintaining complete consistency across the energy supply and demand. Furthermore, about 300 specific technologies, including CCS technologies, are explicitly modeled, and this enables us to assess CO_2 emission reduction measures in detail.

2.2. Assumptions regarding CCS technologies

Table 1 lists the assumptions made regarding the capital costs, required electricity, and CO_2 recovery ratio of CO_2 capture. Technical performances of CO_2 capture technologies from thermal power plants are assumed by feedstock. CO_2 capture from a blast-furnace – basic oxygen furnace (BF-BOF) is also assumed to be a CCS technology in energy end-use sectors. Table 2 summarizes the assumptions on CO_2 storage potential and cost in the world. The CO_2 storage potential share by aggregated region and by sink is shown in Figure 1. CO_2 storage potential is estimated from various sources in the literature, including geographic information system (GIS) data (Akimoto et al. [8]). A deep saline aquifer has the largest share (almost 90%) in the total potential. The former Soviet Union (FUSSR), North America, and Latin America have large CO_2 storage potentials.

Table 1 Assumptions regarding capital costs, required electricity, and CO_2 recovery ratio of CO_2 capture

	Capital cost [US$/(tC/day) in 2000 price]	Electricity consumption [MWh/tC]	CO_2 recovery ratio [%]
CO_2 chemical recovery from coal fueled power	59,100–52,000	0.792–0.350	90
CO_2 chemical recovery from gas fueled power	112,500–100,000	0.927–0.719	90
CO_2 chemical recovery from biomass fueled power	112,500–100,000	2.588–1.144	90
CO_2 physical recovery on gasification plant	14,500	0.801	90–95
CO_2 capture from BF-BOF	70,620–57,600	0.730–0.550	90
	Capital cost [US$/kW in 2000 price]	Generation efficiency[LHV%]	CO_2 recovery ratio [%]
IGCC/IGFC with CO_2 capture	2,800–2,100	33.0–51.0	90–99
Oxy-blown combined cycle with CO_2 capture	1,900–1,400	40.7–50.7	90–99

Note: Cost reduction and energy efficiency improvement are assumed to proceed with time within the ranges indicated in the table.

Table 2 Assumptions regarding potentials and costs for CO_2 storage in the world

	CO_2 storage potential [GtC]	CO_2 storage cost[*1] [US$/tC in 2000 price]
Oil well (Enhanced oil recovery)	30.7	209–252[*2]
Depleted gas well	40.2 – 181.5[*3]	34–215
Deep saline aquifer	856.4[*4]	18–139
Coal bed methane (Enhanced methane recovery)	40.4	99–447[*2]

*1 Cost of CO_2 capture is excluded.
*2 The proceeds from recovered oil/methane are excluded.
*3 40.2 is the initial value in 2020, and the potential increases with natural gas production.
*4 The potential is the "practical" potential, which is 10% and 20% of the "ideal" potential, onshore and offshore, respectively.

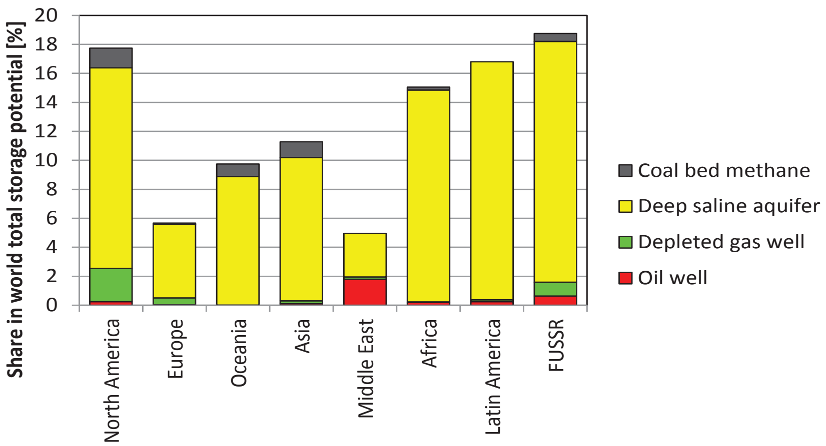

Figure 1 CO_2 storage potential share by aggregated region and by sink

2.3. Assumption regarding implicit discount rate

The assumption regarding the implicit discount rate of technologies is one of the key factors for estimating technology diffusions and marginal CO_2 abatement costs. In general, the implicit discount rates in developing countries are higher than those in developed countries, and those in residential and commercial sectors are higher than those in industrial sectors.

In this study, the implicit discount rates by sector and by region are assumed as indicated in Table 3. Common implicit discount rates are adopted for various technologies including CCS within the sector (Base case). For example, the implicit discount rates of electricity generation sector of developed countries with high per-capita GDP are almost consistent with 10% used as discount rate of CCS in an IEA report [9]. Furthermore, two cases are conducted as pessimistic prospects cases of the technology diffusion barriers to CCS. In these two cases, +5% or +10% penalties on the implicit discount rates are assumed (Stagnant investment case: implicit discount rate +5% and stagnant investment case: implicit discount rate +10%).

Table 3 Assumed implicit discount rates

	Implicit discount rates [%]	
	Upper Limit	Lower Limit
Electricity generation sector	8	20
Other energy conversion sector	15	25
Industrial sector	15	25
Transportation sector	30	45
Residential and commercial sector	30	55

Note: Implicit discount rates for different regions are assumed to be within the above limits, depending on the region's per-capita GDP. The implicit discount rates become smaller according with increases in per-capita GDP.

3. Results and discussions

3.1. Simulation cases for emission reduction levels

Five CO_2 emission reduction cases are considered in this study, as summarized in Table 4. One is the baseline case wherein the CO_2 mitigation policy is not considered. The other four cases with CO_2 emission targets are developed by us based on the concepts of RCPs of the IPCC AR5 (Meinshausen et al. [10]). In this study, equalized marginal CO_2 abatement costs across countries were adopted.

Table 4 Assumed simulation cases for emission reduction levels

	Global energy-related CO_2 emission target [$GtCO_2$/year]			
	2020	2030	2040	2050
Baseline case*	39	47	55	57
CP6.0 case (760 ppm CO_2eq in 2100)	38	45	51	51
CP4.5 case (630 ppm CO_2eq in 2100)	36	40	42	38
CP3.7 case (550 ppm CO_2eq in 2100)	35	35	32	26
CP3.0 case (480 ppm CO_2eq in 2100)	33	29	21	18

* CO_2 emission of the baseline case is the model calculation result obtained without considering the CO_2 mitigation policy. (Marginal CO_2 abatement cost is \$0/tCO_2.)

3.2. Results and discussions

Figure 2 shows sequestrated CO_2 and marginal CO_2 abatement costs for the base case of the implicit discount rate. In the CP6.0 case with low marginal abatement cost (less than \$10/tCO_2), the sequestrated CO_2 is not significantly large until 2050. In the CP4.5 case, CCS becomes a cost-effective option after

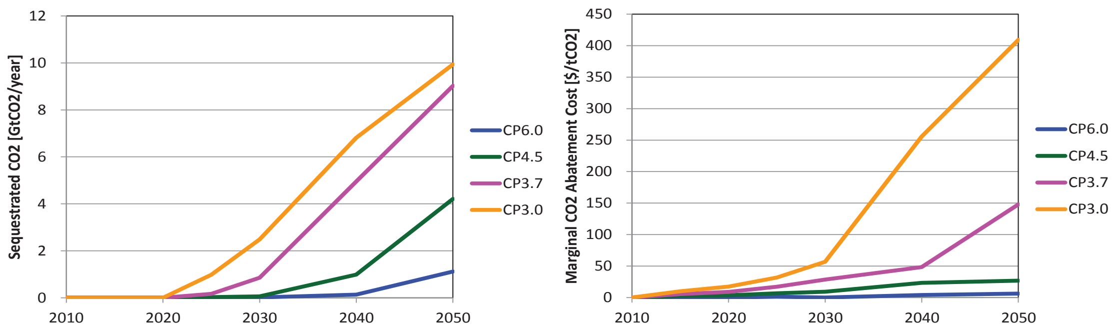

Figure 2 World total sequestrated CO_2 (Left) and marginal CO_2 abatement cost (Right) for the base case

2030 (\$10/tCO_2 to \$30/tCO_2). The sequestrated CO_2 in 2050 is 4GtCO_2/year and the amount corresponds to 23% of the required CO_2 emission reduction from the baseline case. A large portion of the captured CO_2 is sequestrated into an oil well. According to the CP3.7 and CP3.0 cases, CCS will be rapidly used as a cost effective measure for CO_2 emission reduction with a high marginal CO_2 abatement cost of over \$100/tCO_2. The sequestrated CO_2 in these cases is considerably large, being 9GtCO_2/year (CP3.7) and 10GtCO_2/year (CP3.0) in 2050, and the largest sink is a deep saline aquifer. In 2050, CCS diffusion rates for fossil fueled power will reach 85% (CP3.7) and 90% (CP3.0), respectively.

A comparison of world total cumulative sequestrated CO_2 among the three cases of implicit discount rates of CCS is shown in Figure 3. Increases in marginal CO_2 abatement costs for the two stagnant investment cases compared with the costs for the base case, as shown in Figure 2, are not significantly large (less than \$5/tCO_2). In the CP4.5 and CP3.7 cases (\$10/tCO_2 to \$150/tCO_2), the influences of the penalties on the implicit discount rates of the CCS technologies on the cumulative sequestrated CO_2 are larger than those in the other two cases. The cumulative sequestrated CO_2 in the CP4.5 case is 34GtCO_2 (the base case), 23GtCO_2 (the stagnant investment case: implicit discount rate +5%), and 21GtCO_2 (the stagnant investment case: implicit discount rate +10%). The reductions of CO_2 sequestrations for the two stagnant investment cases relative to the base case are 31% and 38%, respectively.

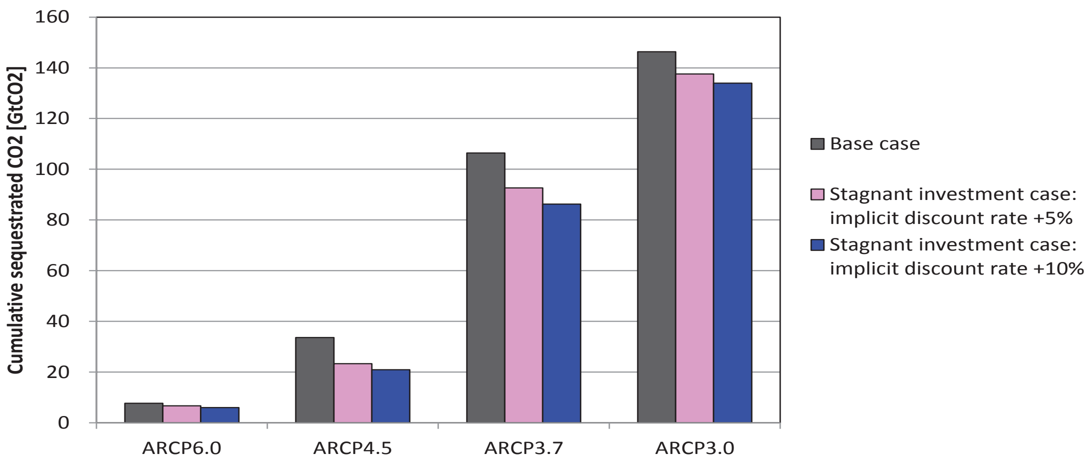

Figure 3 Comparison of world total cumulative sequestrated CO_2 among the three cases of implicit discount rates of CCS technologies

The cumulative CO_2 sequestrations in the CP3.0 case are also affected by the implicit discount rates of CCS technologies, although the impact is less significant compared with the CP4.5 and CP3.7 cases. This is because the marginal CO_2 abatement cost in the CP3.0 case is extremely high, as shown in Figure 2, and CCS is justified as a cost effective measure for CO_2 emission reduction even in the cases with the penalties on the implicit discount rates of CCS technologies.

Table 5 lists the regional cumulative sequestrated CO_2 for the base case and the stagnant investment case (implicit discount rate +5%). The cumulative CO_2 sequestrations in North America (the United States), Asia (China, India, and Indonesia), and the Middle East are relatively larger than those in other regions of the world, as evident from the data given in Table 5. When the penalties on the implicit discount rates of the CCS technologies are considered, the cumulative CO_2 sequestration in these three regions is found to be reduced.

CCS diffusion is significantly affected by the implicit discount rates that reflect the technology diffusion barriers in the real world. Therefore, of course R&DD efforts for achieving cost reduction and energy efficiency improvement of CCS are very important, but it is not enough to achieve large CCS diffusion. There are many policy measures to reduce CO_2 emission. Carbon tax which is the one of top-down type policy approach is cost efficient in economic theory. However, the tax cannot be formulated without considering the technology diffusion barriers. The required tax will be higher price for ambitious CO_2 emission reduction, and it will be difficult to accept for most countries. Therefore, bottom-up type policy approach, e.g., CO_2 intensity targets, will be useful to diffuse CCS and other global warming technologies (Akimoto et al. [11]). Such approaches will encourage investment decision with low implicit discount rates. Furthermore, the liability for very long term CO_2 storage and the public acceptance which is affected by this liability are important issues for the diffusion of CCS, as mentioned in the introduction. The large-scale CCS is not an experienced technology at this time, so that steady efforts to solve these issues are important, e.g., public relations of CCS with energy and environmental education.

Table 5 Cumulative sequestrated CO_2 for the base case and the stagnant investment case (+5% implicit discount rate) by aggregated region

	CP6.0	CP4.5	CP3.7	CP3.0
Base case				
North America	1.9	11.5	27.0	32.1
Europe	0.3	3.2	11.8	21.7
Oceania	0.2	1.5	3.5	5.9
Asia	4.5	8.2	35.1	51.5
Middle East	0.0	5.3	14.8	16.4
Africa	0.0	0.9	7.1	7.5
Latin America	0.5	1.1	2.9	4.2
FUSSR	0.3	1.8	4.2	7.1
Stagnant investment case (implicit discount rate +5%)				
North America	1.4	8.4	20.9	30.5
Europe	0.2	2.4	10.3	20.1
Oceania	0.0	1.1	2.9	5.1
Asia	4.3	6.1	31.5	50.5
Middle East	0.0	3.2	13.5	14.8
Africa	0.0	0.2	6.8	6.4
Latin America	0.5	0.6	2.7	3.9
FUSSR	0.3	1.4	4.0	6.5

4. Conclusion

An analysis of diffusion of CCS while considering technology diffusion barriers has been performed using the DNE21+ model. CCS technologies are expected to be among the various cost effective measures that will be used for ambitious CO_2 emission reduction. However, the widespread use of CCS technologies cannot be guaranteed, owing to real-world technology diffusion barriers, as quantitatively discussed in this paper.

Not only R&DD efforts, the bottom-up type policy approach such as CO_2 intensity target will be important to achieve the diffusion of CCS and other global warming technologies through removal of the existing technology diffusion barriers. Furthermore, improvements in the liability for very long term CO_2 storage and public acceptance are also required for CCS.

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